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AN MHD STUDY OF THE INTERACTION BETWEEN THE
SOLAR WIND AND THE INTERSTELLAR MEDIUM

Principal Investigator:

R. S. Steinolfson
Dr. R.S. Steinolfson
Staff Scientist
Southwest Research Institute
6220 Culebra Road
San Antonio, TX 78238-5166
E-mail: rich@solar.space.swri.edu
(210) 522-2822

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SUMMARY

The overall objective of this research program is to obtain a better understanding of the interaction between the solar wind and the interstellar medium through the use of numerical solutions of the time-dependent magnetohydrodynamic (MHD) equations. The simulated results will be compared with observations where possible and with the results from previous analytic and numerical studies. The primary progress during the first 3 years has been to develop codes for 2-D models in both spherical and cylindrical coordinates and to apply them to the solar wind/interstellar medium interaction. Computations have been carried out for both a relatively simple gas-dynamic interaction and a flow-aligned interstellar magnetic field. The results have been shown to compare favorably with models that use more approximations and to modify and extend the previous results as would be expected. The simulations have also been used along with a data analysis study to provide a quantitative estimate of the distance to the termination and bow shocks. Work has also been initiated on the development of a 3-D MHD code in spherical coordinates.

I. SCOPE OF THE INVESTIGATION

The interaction of the solar wind with the interstellar medium has received increased interest recently due to improved observations of the local interstellar medium and to the fact that a deep space probe may soon intersect the shock terminating the supersonic solar wind flow. Previous theoretical and computational efforts at studying the interaction have been hampered by a lack of observational guidance and have not been developed to the level necessary to determine the quantitative effects of some of the important known physical processes on the global interaction. When used in conjunction with present and forthcoming observations, the present models may assist in determining the effects of the relevant physical processes. In addition, they may also indirectly be able to place bounds on the currently unknown or speculative values of physical quantities in the local interstellar medium as well as the location of the termination shock and the heliopause.

Time-dependent, multi-dimensional, gas dynamic and MHD codes will be used to study this interaction through the use of a relaxation technique in which an assumed non-equilibrium initial state approaches a final steady-state equilibrium. Although the codes incorporate numerous physical mechanisms, they can optionally be included in individual studies. The approach is to begin with simple cases, to compare with applicable earlier work and build on the previous results, and to separately include effects, such as the interstellar and interplanetary magnetic fields, thereby providing a consistent basis from which to quantify the effects of a particular mechanism.

The overall objective is to achieve a better understanding of the processes involved in the interaction. Some of the more specific issues that this study will address are (a) the influence of various thermodynamic, dynamic, and magnetic conditions in the interplanetary and interstellar mediums on the location of the termination shock and the heliopause, (b) the differences between two-dimensional and three-dimensional models, (c) the complete self-consistent global interaction including the tail region, and (d) the effect of both temporal and spatial gradients in the solar wind. Model predictions will be compared with observations whenever possible, and the available observations will be used to provide guidelines on model input values for the solar wind and interstellar medium.

II. PROGRESS DURING CURRENT REPORTING PERIOD

As mentioned previously, the MHD simulations will ultimately be performed using a three-dimensional model. However, due to the large memory and computation time requirements for the 3-D simulations, the initial computations have been carried out using a 2-D model. These preliminary 2-D simulations serve several purposes in addition to providing useful physical insight. They will be used to determine some of the numerical parameters required in the 3-D studies, such as the grid spacing needed in order to resolve particular features and the damping that must be including to remove high-

frequency oscillations. Furthermore, the first computations neglected the magnetic field so the results could be compared directly with those from more approximate analyses.

Two separate codes for the 2-D model have been developed. In one the equations are solved in the r - θ plane of a cylindrical coordinate system in which the axial (z) axis is perpendicular to the interstellar flow direction. For the second the equations are solved in a spherical coordinate system. The two coordinate systems are used in order to allow greater flexibility for the inclusion of a magnetic field within the confines of a 2-D model. A variable grid spacing is incorporated in the radial direction to provide better resolution in the solar wind portion (and near the termination shock) of the interaction. Each of the studies carried out during this reporting period are discussed in more detail below. All of these results either have been or will be written up in papers and presented at international and/or national scientific meetings.

The primary effort performed during this reporting period was to complete a study (summarized below) done in collaboration with Dr. Don Gurnett of the University of Iowa involving quantitative estimates of the distances to the termination shock and the heliopause. Heliospheric radio emission events observed by Voyagers 1 and 2 have been interpreted by Gurnett et al. [*Science*, 262, 199, 1993] as occurring when a strong interplanetary shock interacts with the heliopause. The interplanetary shock can be related to large Forbush decreases recorded by neutron monitors at Earth and by cosmic ray detectors on Pioneer and Voyager spacecraft. The time delay between the Forbush decrease at the Earth and the radio emission event is about 408 days. The shock propagation speed as determined from the Pioneer and Voyager data is estimated to be within the range of 600 to 800 km/sec, with some preference for the higher value. These observational results have been used as the foundation for a numerical study to simulate the propagation of a solar-generated shock wave through a dynamic equilibrium solution for the solar wind/interstellar medium interaction. A series of parametric studies is used to find the equilibrium solution in which a shock propagating at a selected speed within the observed range (600-800 km/sec) results in the observed time delay (~408 days). The solar wind conditions at 1 AU were fixed at $n_e = 5 \text{ cm}^{-3}$, $T = 10^5 \text{ }^\circ\text{K}$, $v = 400 \text{ km/sec}$, and the interstellar conditions were fixed at $T = 10^4 \text{ }^\circ\text{K}$, $v = 25 \text{ km/sec}$. For a given interplanetary shock speed the interstellar density and magnetic field magnitude were varied until the above time delay was obtained. The termination shock is at a distance of 115 AU, and the heliopause is at 160 AU for an interplanetary shock speed of 800 km/sec. These distances reduce to 92 AU for the termination shock and 128 AU for the heliopause when the shock speed is reduced to 600 km/sec. A paper based on this study has been prepared and submitted [Steinolfson and Gurnett, 1994].

Studies have been initiated with a magnetic field in the interstellar medium. When the relative motion between the solar system and interstellar medium is supersonic, the presence of the magnetic field causes the downstream portion of the termination shock to vanish downstream. Runs are presently being carried out for subsonic relative motion.

The 3D MHD code has been developed and is currently undergoing various tests before being used for specific applications. A magnetic field in the solar wind can be included in this code in addition to a magnetic field in the interstellar medium. With a magnetic field in both the interstellar medium and the solar wind, the interaction is inherently three dimensional.

A significant part of any multi-dimensional study such as that discussed here is the development of suitable graphics to assist in the physical interpretation of the simulated results. With partial support from the present grant the pv-wave and data explorer software packages have been and continue to be extended to produce 2-D and 3-D displays of particular interest to the present work. For instance, the ability to generate shaded 3-D plots of a given value of a physical quantity have been developed. Spatial plots of overlays of magnetic field lines, velocity vectors, and velocity streamlines on the distribution of a thermodynamic quantity such as the particle density have also been developed.

III. CUMULATIVE LIST OF PRESENTATIONS AND PAPERS

- R.S. Steinolfson, A numerical study of the interaction between the solar wind and the interstellar medium, **Solar Wind VII**, Goslar, Germany, 16-20 September 1991.
- R.S. Steinolfson and T.E. Holzer, A numerical study of the interaction between the solar wind and the interstellar medium, **XVII General Assembly of the European Geophysical Society**, Edinburgh, Scotland, 6-10 April 1992.
- R.S. Steinolfson, V. Pizzo, and T. Holzer, The interaction of the solar wind with the interstellar medium, **EOS**, **73**, 445, 1992.
- R.S. Steinolfson and V. Pizzo, Gas-dynamic simulations of the two-shock model of the solar wind/interstellar medium interaction, **EOS**, **74**, 234, 1993.
- R.S. Steinolfson, The interaction of the solar wind with the interstellar medium, **XXIV General Assembly of the International Union of Radio Science**, Kyoto, Japan, 25 August-2 September 1993.
- R.S. Steinolfson, V. Pizzo, and T. Holzer, Gas dynamic models of the solar wind/interstellar medium interaction, **Geophys. Res. Lett.**, **21**, 245, 1994.
- R.S. Steinolfson, Termination shock response to large-scale solar wind fluctuations, **J. Geophys. Res.**, in press, 1994.
- R.S. Steinolfson and D.A. Gurnett, Termination shock and heliopause distances estimated from coordinated simulations and data analyses, **EOS**, **74**, 487, 1993.
- R.S. Steinolfson and D.A. Gurnett, Distances to the termination shock and heliopause from a simulation analysis of the 1992-93 heliospheric radio emission event, **J. Geophys. Res.**, submitted, 1994.
- R.S. Steinolfson and D.A. Gurnett, Distances to the termination shock and heliopause from a simulation analysis of the 1992-93 heliospheric radio emission event, **Second Pioneer-Voyager Symposium.**, Durham, New Hampshire, 31 May-3 June 1994.